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Rapid Thermal Ice Penetrator*

Arctic Field Test Results for an "A" Size Configuration

FINAL REPORT

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Ocean Systems Research, Inc. has developed a Rapid Thermal Ice Penetrator (patent pending) with a demonstrated capability to penetrate thick ice at rates in excess of 6 feet per minute. This report addresses the results of Arctic field testing of 6 ice penetrators complete with autonomous uprighting devices and dummy payloads. The testing proved the overall feasibility of the solid propellant ice penetrator and uprighting device concept to rapidly and autonomously penetrate thick Arctic ice. The actual thickness of ice penetrated was 10 feet, 4 inches in a time of 120 seconds. Hole diameter was approximately 7 inches.

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1.0 EXECUTIVE SUMMARY

In April 1991 OSR successfully demonstrated an ability to penetrate 10 feet of Arctic ice in under 2 minutes. The testing took place at the APLIS ice camp under the sponsorship of the Naval Air Development Center and the Office of Naval Technology.

The testing proved the overall feasibility of the solid propellant ice penetrator and uprighting device concept to rapidly and autonomously penetrate thick Arctic ice. The actual thickness of ice penetrated was 10 feet 4 inches in a time of 120 seconds. The hole produced was approximately 7 inches in diameter and appeared to be absolutely vertical.

The late program start (brought on by delays in funding) imposed several design compromises that are discussed in detail in this report. Specifically, the schedule simply did not allow sufficient time to incorporate a new higher energy propellant or allow sufficient testing to select a single nozzle configuration for Arctic testing. As a result the 6 prototypes delivered for Arctic testing were longer than 36 inches and included 3 different nozzle designs. In order to stay within the "A" size configuration (i.e., 36 inches), and allow sufficient volume for a sensor payload, it is planned that a propellant with a 40% higher energy content per pound be used. The design and testing of an ice penetrator incorporating the higher energy propellant must, therefore, be performed prior to, or as part of the development of a flightweight air deployable "A" size unit.

2.0 BACKGROUND

Several ice penetration techniques have been examined in the past few years in an attempt to develop an ice penetrating environmental sensor. The two concepts having received the most attention are kinetic penetration and thermochemical penetration.

Kinetic penetration imposes tremendous deceleration upon impact with the ice which seriously affects the design of the delicate sensors/electronics currently in use. Other problems include the difficulty in maintaining communications with the device once it penetrates the ice, a size that is too large for existing launch tubes, and restrictive launch envelopes.

The present thermochemical techniques have not achieved penetration rates that are rapid enough to provide tactically useful designs. Penetration rates of 30 minutes to 1 hour for 10 feet of ice are the norm.

In June of 1990 OSR received a 2 phased contract (N62269-90-C00546) from the Naval Air Development Center in Warminster, PA to assess the feasibility of adapting their rapid thermal ice penetrator technology to an "A" size configuration (5 inch O.D.) for an Arctic environmental sensor. The stated goal of this program was to achieve penetration through 10 feet of ice in under 2 minutes.

Phase I of the contract, completed in October 1991, proved the feasibility of the "A" sized design to achieve penetration rates in excess of 5 feet per minute. These tests were performed through 4 to 5 foot thick blocks of ice at Thiokol's facility in Elkton, Md.

Based upon the successful test results achieved during Phase I, coupled with analytical predictions which clearly indicated equivalent success when extrapolated to 10 foot ice thicknesses, the decision was made to proceed to Phase II. This report addresses Phase II.

Phase II was to be an intensive 8 month test program, beginning in October 1990, incorporating a new 40% higher energy propellant and including a highly structured in-house test program to optimize nozzle design. Phase II was to culminate in an Arctic test of 6 units (scheduled for April 8-10, 1991) designed to upright themselves and penetrate 10 feet of ice in under 2 minutes.

Due to funding delays, however, the program was reduced in scope, eliminating the introduction of the higher energy propellant and reducing the number of in-house tests from 7 to 3. The schedule for Arctic testing of the 6 units in April 1991, however, remained unchanged.

3.0 HARDWARE DESCRIPTION

3.1 Ice Penetrator Motors

The program called for a total of 9 motors, 3 for in-house testing and 6 for Arctic testing. In order to minimize schedule risk and to mitigate the effect of any unforseen fabrication problem or error, sufficient components for 2 spare motors were fabricated.

In order to meet the tight fabrication, testing, and delivery schedule, virtually all of the major design parameters had to be

resolved very early in the program. The schedule allotted less than two weeks from performance of in-house testing (through the 10 foot ice blocks) to shipment of the motors to the Arctic. This meant that parameters such as rocket motor dimensions, insulator type/thickness, propellant volume, overall nozzle closure design, etc., would have to be identical for both the in-house and Arctic test units. The design had to flexible enough, however, to allow a variation in the number, size, and orientation of the exhaust nozzles.

The baseline motor configuration is shown in Figure 1. The innovative nozzle closure design was selected to allow complete assembly prior to the machining of the nozzles. Thus all of the nozzle closure assemblies could be completely fabricated (without drilled nozzles) to allow the required variation once in-house test results and analytical model predictions became available.

The baseline ice penetrator motor was approximately 45 inches long and weighed 41.7 pounds. It contained 21.5 pounds of propellant with an average energy content of 2250 Btu/Lbm. Predicted chamber pressure of the motors varied from approximately 300 to 500 psia depending upon the combined throat area of the nozzles for each particular design option. Burn time predictions for the motors (which varies as a function of chamber pressure/throat area) ranged from 110 to 145 seconds. The calculated net axial thrust of the motors ranged from 2 to 17 pounds.

The nozzle configurations were selected as a trade-off between

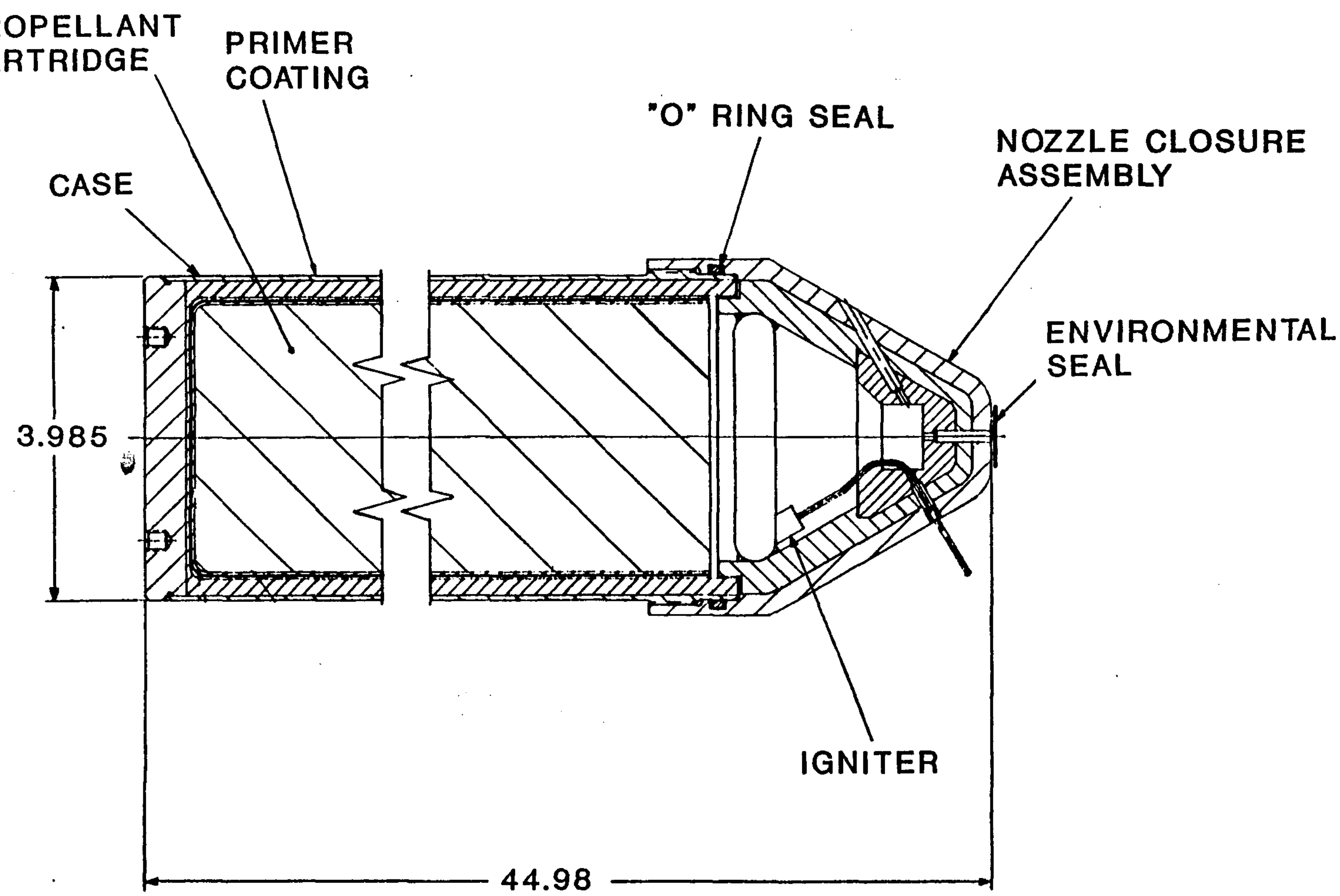

Figure 1 Ice Penetrator Motor

net axial thrust, ice melting efficiency, design simplicity, and potential for nozzle clogging. The baseline nozzle closure design (See Figure 2) contained a total of 9 nozzles as follows: 1 central nozzle (0 degrees), 4 forward facing nozzles at 60 degrees, and 4 reverse facing nozzles at 120 degrees. The diameters of each of the 9 nozzles were varied based in part upon our analytical model's performance predictions. In addition, 2 alternate nozzle configurations were also tested, shown in Table 1 as Alternate 1 and 2.

	NOZZLE LAYOUT			
	0 degrees	60 degrees	90 degrees	120 degrees
Baseline	1	4	none	4
Alt 1	1	4	4	none
Alt 2	1	none	none	4

Note: Nozzle throat diameter also varied for each configuration

Table 1 Nozzle Configurations Tested

The 5 forward facing nozzles on Alternate 1 were located identically to those in baseline configuration. The four remaining nozzles directed their exhaust normal to the vertical axis of the motor thereby having a neutral effect on thrust. Alternate 2 contained only 5 nozzles, one central nozzle (0 degrees) and 4 reverse acting nozzles at 120 degrees. The other major difference

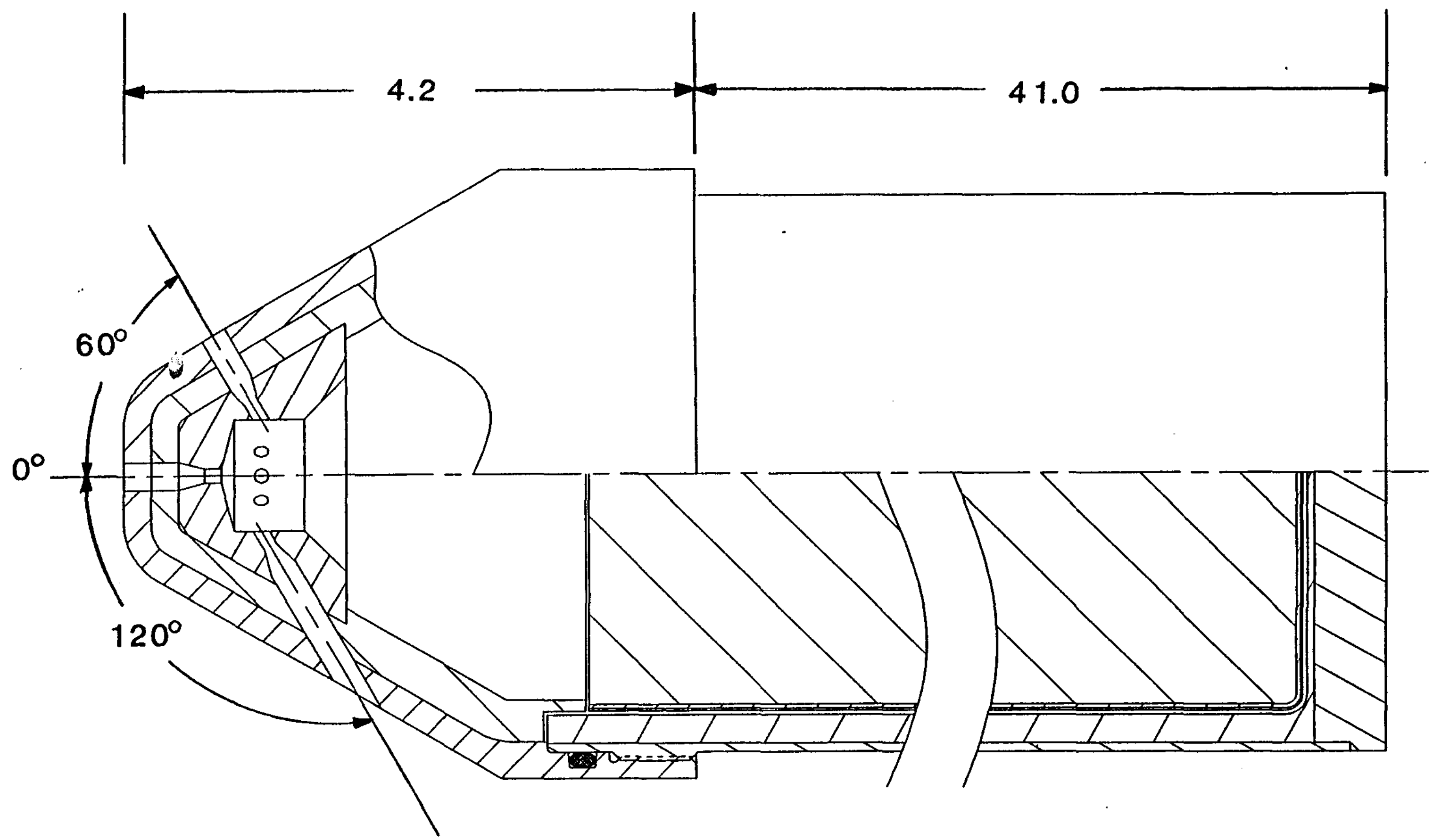

Figure 2 Baseline Nozzle

in Alternate 2 is that the central nozzle was significantly larger in diameter than any other motor (directing more than 70 percent of the exhaust products) to eliminate the possibility of nozzle clogging.

After the potential for nozzle clogging was identified (as a result of the 3 in-house tests) a minor modification was made to the forward face of the penetrator, that is, the flat area surrounding the central nozzle. The calculated pressure at nozzle exit was approximately 40 psi. It was postulated that with the total penetrator weight (approximately 40 pounds) resting on the flat central nozzle face (area about 1 square inch) that flow stoppage could occur in the forward nozzle thereby diverting the exhaust to the remaining 8 nozzles. Since keeping the forward nozzle clear was critical for good penetration, the following means of preventing the forward nozzle from becoming clogged was implemented. The flat area surrounding the central nozzle was therefore scored with an "X" pattern approximately 0.100 inches deep to ensure an escape path always existed for the central nozzle despite it being placed firmly against the ice.

3.2 Uprighting Device

The uprighting device was designed to upright a 36.0 inch long, 50 pound device from horizontal to vertical in under 4 seconds. Since the end product will see only one time use and then be discarded, every attempt was made to make its cost almost negligible in comparison to the ice penetrator and sensor payload. In addition, the rugged operating environment is simply not

conducive to closely toleranced parts whose performance could change with temperature. Therefore it was determined that no complex air cylinders, hydraulics, sliding "O" ring seals, etc. be utilized. Lastly, the device had to be lightweight. With an overall system weight limit of 50 pounds, more weight for the uprighter meant less available for the penetrator and sensor payload.

The uprighting device serves two major functions. First, upon landing on the ice, the uprighter functions to erect the penetrator to a vertical position with respect to the ice. Secondly, the uprighting device serves as a guide tube, maintaining the penetrator in a vertical position as it enter the ice.

The uprighting device (See Figures 3 and 4) surrounds the ice penetrator and sensor payload. The entire sensor package, including the uprighter is designed to fit within the standard envelope dimensions for an "A" size sonobuoy, namely 4 7/8 inch O.D. and 36 inches in length. The uprighting device itself weighs approximately 10.5 pounds. The I.D. of the uprighter is 4.05 + .02, - .00, thus leaving ample clearance for the motor to slide through unimpeded. (Motor O.D. is 4.00 +.00, -.01.)

A combination of multiple leaf springs and a single coil spring provide the motive force for uprighting the unit. With the exception of the leaf and coil springs which are made of C1095 carbon steel, the unit is fabricated from 6061-T6 aluminum alloy. Pivoted joints are held in place with 3/32 diameter spring pins and all remaining fasteners are 6-32UNC - 24 stainless steel socket

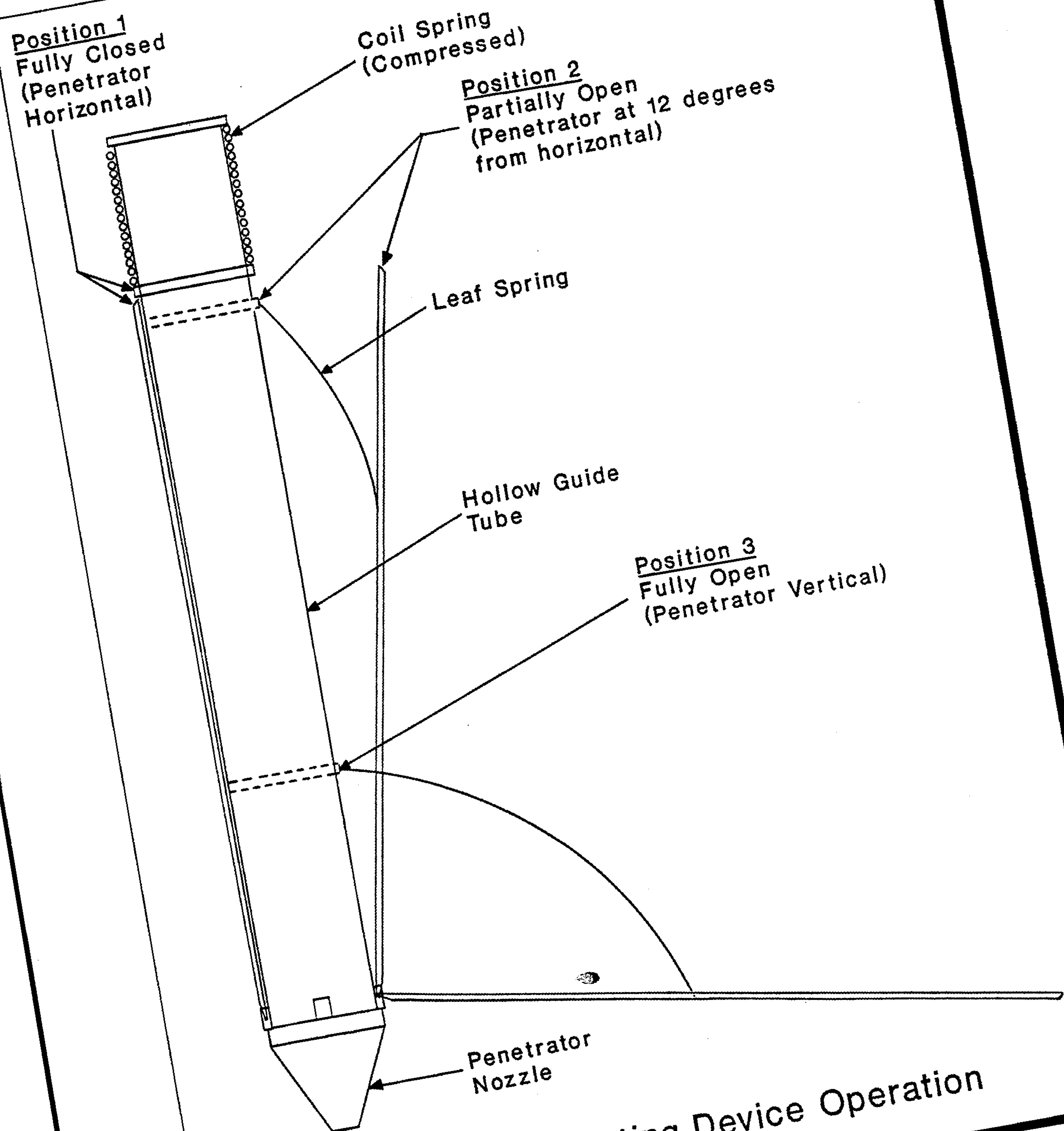

Figure 3 Uprighting Device Operation

Figure 4A Uprighting Device in Closed Position
(Shown on pallet with ice penetrator inserted, prior to installation of release mechanism band clamp.)

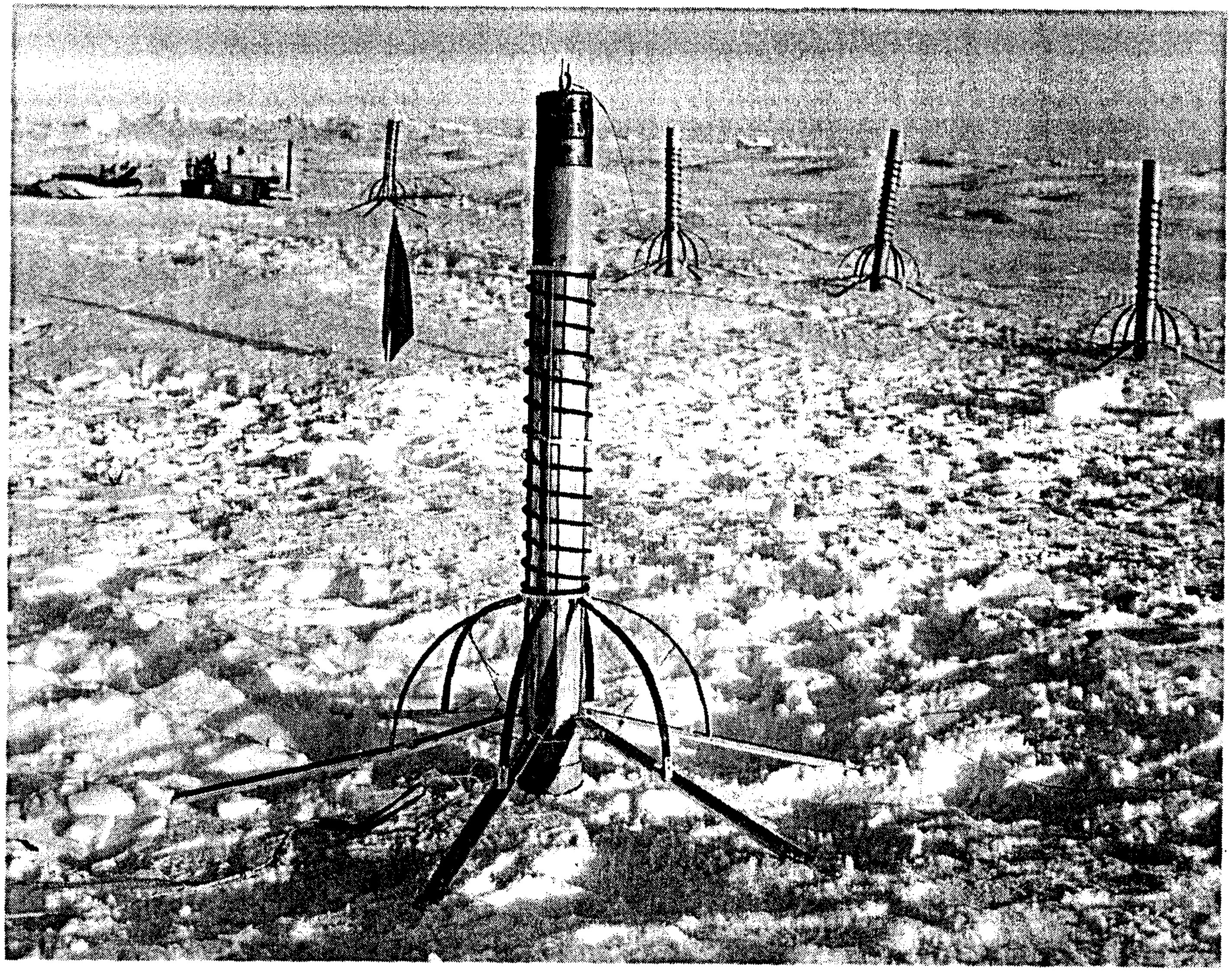

Figure 4B Uprighter Device in Open Position

head cap screws.

The device is designed to operate as follows:

1. The unit is placed horizontally on the surface of the ice (eventually the unit is to be dropped from an airplane).
2. The release mechanism severs the circumferential band holding device in the closed position.
3. Leaf springs provide the initial force to upright the device to approximately 12-15 degrees from the horizontal.
4. Once the device is uprighted greater than 12 degrees from horizontal the energy stored in the coil spring has sufficient mechanical advantage to bring the entire unit to a vertical orientation.
5. A very simple low cost, damping device imparts sufficient drag on the spring to prevent the device from overshooting the vertical position. The damping consisted of drawing two small diameter steel cables through holes as the coil spring expanded.

3.2.1 Uprighting Device Component Description

Leaf Springs

The leaf springs provide the initial force required to lift one end of the penetrator (the end opposite the nozzle) approximately 7 inches off the ground (or approximately 12 degrees from the horizontal). The leaf springs are made from blue tempered spring steel (Rockwell C49-51), 0.94 inches thick by 0.625 inches wide. The free length of the springs is 13.7 inches with a deflection of 2.25 inches. Flattened length was 14.5 inches.

Each leaf spring, when fully compressed, generates a force of 54.5 pounds. Since the required force (calculated) is 43 pounds, adequate margin exists to ensure proper system operation. Once the leaf spring lifts one end of the penetrator the required 7 inches, sufficient mechanical advantage is then available for the coil spring to bring the penetrator vertical.

<u>Coil Springs</u>

The coil spring is made of C1095 carbon steel wire. At its compressed length of 6.0 inches it generates a force of 200 pounds. The coil spring is still under compression at its extended length of 23.25 inches, generating about 57 pounds of force. The average spring constant (K) is 8.28 pounds per inch.

<u>Actuator/Release Mechanism</u>

OSR used its proprietary amorphous metal release mechanism as the actuator for the uprighting device. The actuator takes advantage of the drastic change in material properties of the cable as it is heated above its recrystallization temperature. The amorphous metal cable exhibits a very high strength (greater than 500 KSI tensile) when in its amorphous phase, however, once its temperature is raised above a critical point (recrystallization temperature) it reverts to its crystalline state unable to withstand any appreciable shear loading.

The actuator operates as follows:

A small length of amorphous metal a cable is used to secure a stainless steel band strap around the 6 spring loaded legs thus maintaining it in the closed position. When it is desired to

release the legs (i.e., upright the device) an electrical current from a 9.4 volt battery pack is passed through the cable. Due to the very high resistance of the amorphous metal cable it rapidly heats causing it to fail in less than one second, thus releasing the spring loaded legs, forcing the penetration to a vertical position.

4.0 ICE PENETRATOR TESTING

4.1 In-House Tests

Three ice penetrator motors were tested for penetration through 10 feet of ice at Thiokol's facility in Elkton, MD. The test apparatus was set up as shown in Figure 5. A 10 foot x 3 foot x 3 foot block of ice was fabricated for each test. A hollow aluminum tube (4.060 I.D.) was placed on top of the ice to simulate the uprighting device. A 1/32 diameter wire was attached to a flange at the rear of the penetrator via a swivel hook. The opposite end of the wire was connected to a constant tension payout indicator to provide displacement data. Provisions were also available for adding weights to the rear of the penetrator motor via four threaded mounting holes. Video cameras were positioned at various angles to monitor ice penetrator performance during the tests. Fans were strategically placed to remove smoke/vapor thus allowing better video coverage.

The ice penetrator motors used for the Phase II tests were approximately 40 inches long (approximately 45 inches long including the nozzle). A higher energy propellant (slated for

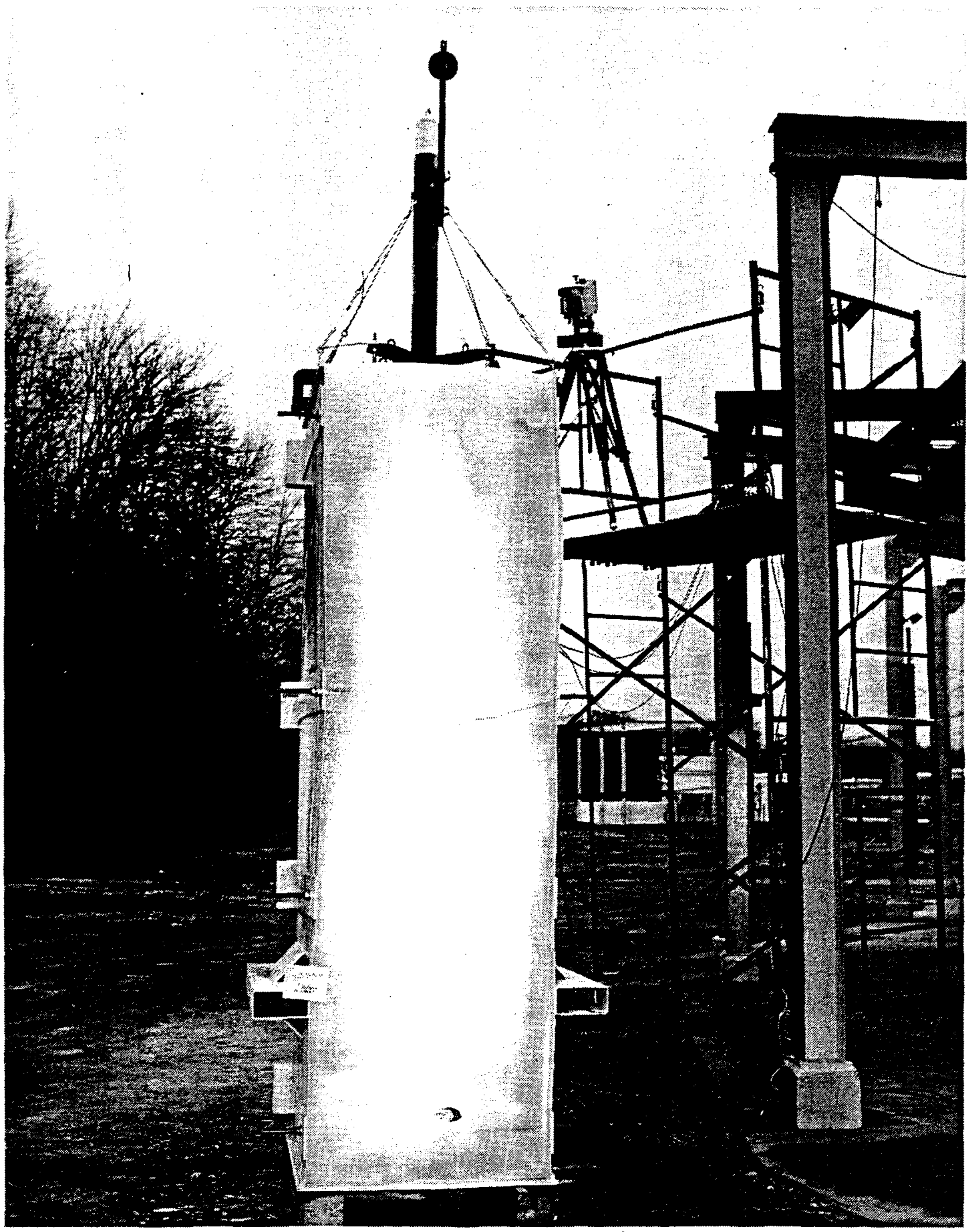

Figure 5 In-House Test Arrangement
(Ice Penetrator mounted in hollow tube atop 10 foot tall by 3 foot square ice block.)

future tests) should reduce this length to on the order of 25 to 26 inches including the nozzle. The increased motor length for these tests had the following effects:

1. The increased penetrator volume displaces more water making it about 5 pounds more buoyant, therefore an additional 5 pounds of weight had to be added to the penetrator.
2. The increased length raised the center of gravity of the penetrator both during and after uprighting. This tended to make the system less stable.

4.1.1 In-house Test Results

A matrix showing configurations tested both in-house and in the Arctic is provided in Figure 6. The first test motor was tested on 22 March 1991. It had 9 nozzles, 1 central nozzle (0 degrees), 4 forward facing nozzles at 60 degrees and 4 reverse facing nozzles at 120 degrees. Calculated burn time was 112 seconds, predicted thrust was 11.0 pounds. Approximately 5 pounds of weight was added to make up for the buoyancy effects of the large canister at end of burn. Actual burn time was 128 seconds. The motor penetrated approximately 7 feet of ice at which time it appeared to bob up and down due to buoyancy. The final penetration depth was about 8.0 feet.

Test number two was also performed on 22 March 1991. Again this motor had a total of 9 nozzles, the central and forward facing nozzles were the same as in Test 1. The four remaining nozzles directed their exhaust normal to the vertical axis of the motor thereby having a neutral effect on thrust. The calculated thrust

	QTY Tested	Nozzle Description	Thrust (Calc.)	Burn Time (Calc.)	Max Thickness Penetrated
In-House Testing	2 (Baseline)	1@ 0 degrees, .144 dia 4@ 60 degrees, .085 dia 4@ 120 degrees, .085 dia	11 Lbs.	112 sec.	8.0 feet
	1 (ALT 1)	1@ 0 degrees, .144 dia 4@ 60 degrees, .085 dia 4@ 90 degrees, .085 dia	17 Lbs.	112 sec.	2.5 feet
Arctic Testing	3 ((MOD 1)	1@ 0 degrees. .209 dia 4@ 60 degrees, .085 dia 4@ 120 degrees, .085 dia	11 Lbs.	146 sec.	9.5 feet
	2 (MOD 2)	1@ 0 degrees, .144 dia 4@ 60 degrees, .085 dia 2@ 120 degrees, .085 dia 2@ 120 degrees, .144 dia	2 Lbs.	150 sec.	3.0 feet
	1 (ALT 2)	1@ 0 degrees, .281 dia 4@ 120 degrees, .085 dia	17 Lbs.	154 sec.	10.3 feet

Figure 6 Phase II Ice Penetrator Test Matrix

and burn time was 17 pounds and 112 seconds respectively. Approximately 25 pounds of inert weight was added to the motor in this test. The actual burn time of the motor was 98 seconds. The motor penetrated approximately 2.5 feet of ice then continued its burn without further penetration. Upon inspection following the test it was determined that a heavy wire had mistakenly been frozen into the ice thereby inhibiting forward movement. Because of this unexpected problem, a third motor test was performed at Thiokol on March 27 utilizing one of the spare motors. This third test motor was similar to the one used in Test 1. Approximately 25 pounds of inert weight was added to this motor to ensure that it would overcome thrust and buoyancy effects with a very large margin. Unfortunately, the motor penetrated approximately 3 feet of ice then continued to burn without further penetration. Actual burn time was 123 seconds. Post test inspection revealed that the central nozzle had become clogged during the burn thereby severely limiting additional penetration.

After reviewing the results from the three in-house tests, and comparing them with analytical predictions, several possible problem areas were identified. Nozzle clogging was observed in all three tests to a varying degree. Some nozzle clogging is acceptable, however, clogging of the central nozzle appeared to be very detrimental. Analysis of the material clogging the nozzle revealed a high glass content. Since glass is a major component of the selected insulator, it became clear that an alternate insulator should be used in future designs. Unfortunately, the motors

scheduled for Arctic testing were already built with the identical insulating material. The other factor affecting penetration rate was the balance between buoyancy and thrust.

Since there was insufficient time to perform a fourth test prior to the April 4 shipping date, it was determined that the only way to ensure successful penetration through 10 feet of Arctic ice in under 2 minutes was to send 3 different nozzle configurations for Arctic testing. The configurations and quantities sent are described in Figure 6.

As an added precaution to prevent clogging in the central nozzle, the flat section surrounding the central nozzle was scored with a "X" pattern approximately .100 deep to ensure an escape path always existed for the central nozzle exhaust, despite it being placed firmly against the ice.

4.2 Arctic (Field) Testing

Six ice penetrator motors and six uprighting devices were delivered to the APLIS ice camp for testing on April 8-9, 1991. All 6 uprighting devices were identical. The 6 ice penetrator motors were identical with respect to the following:

Length:	44.98
Diameter:	
Motor Body:	3.95
Nozzle:	4.37
Total Weight:	41.7 lbs.
Propellant Weight:	21.2 lbs.
Propellant Energy Content:	2250 Btu/Lb

The only difference in the 6 Arctic test penetrators was the number, size, and location of the individual nozzles in the nozzle closure. The combination of the above 3 variables affects chamber pressure, burn time, and net axial thrust. A description of each configuration as well as quantities tested is provided in Figure 6.

4.2.1 Ice Penetrator Test Results (Arctic)

The first unit, tested on the evening of 8 April, was the baseline design with an increased diameter central nozzle (designated MOD 1 in Figure 6). It had a total of 9 nozzles with a calculated burn time of 146 seconds. After ignition, the penetrator, as expected, began to slide downward through the uprighting device as the ice melted. At approximately 50 seconds, just as the penetrator was to clear the bottom of the uprighting device and proceed independently, all downward notion stopped. The ice penetrator then continued to burn for a total of approximately 155 seconds, with no additional forward movement. Upon inspection following the test, it was noted that the ice penetrator had become mechanically hung up in the uprighter by two of the bolt heads of the bolts used to attach the dummy payload to the rear of the penetrator (see Figure 7). Although the penetrator never left the uprighting device, a hole depth of 5 feet was measured (4 feet, 3 inches of ice, the rest being snow cover) with a diameter of 11-12 inches. Needless to say, the bolt heads on the above-mentioned long bolts were cut off and ground smooth for all subsequent tests.

Test number two (and all subsequent tests) were performed on 9 April, the following day. Test number two utilized a penetrator

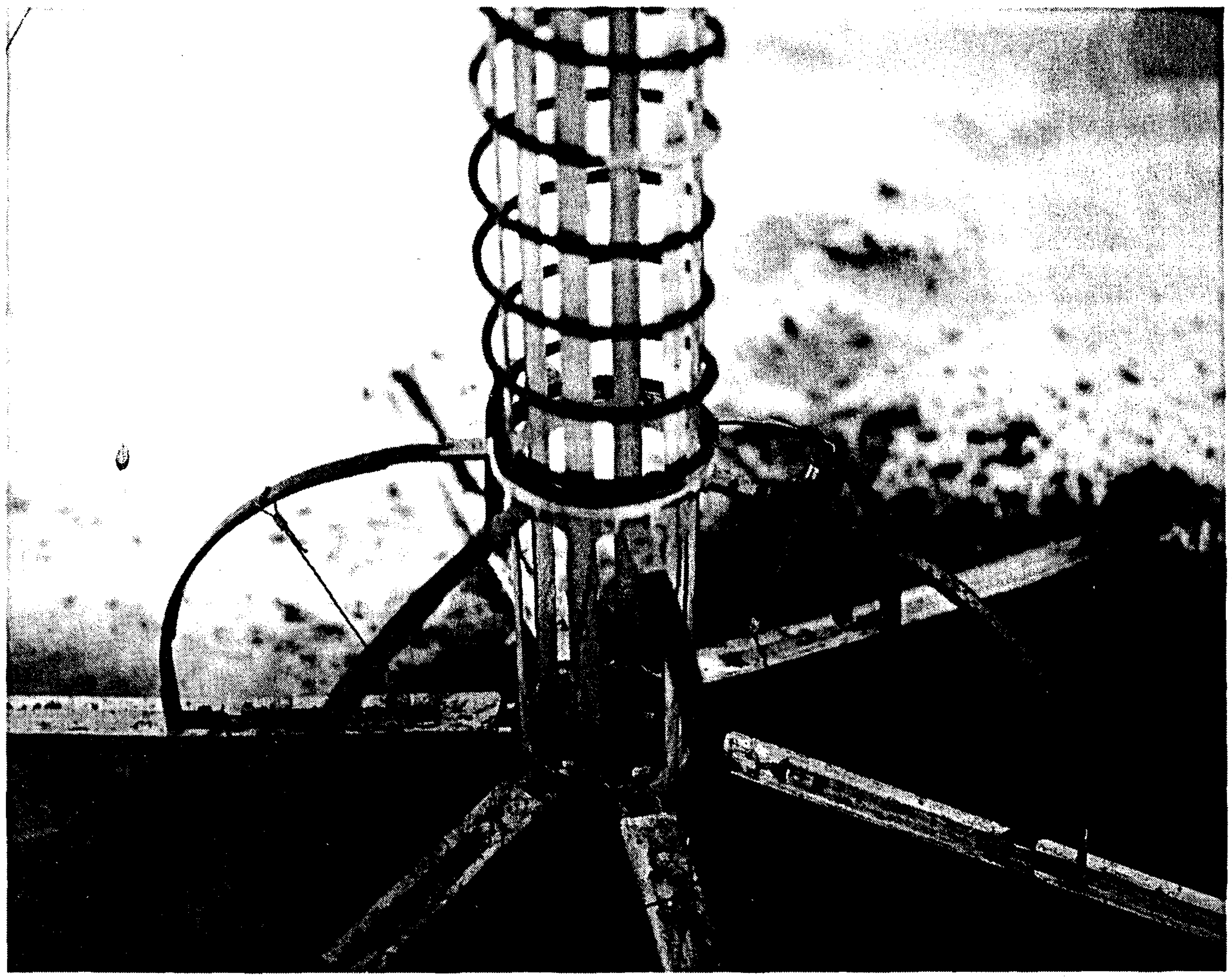

Figure 7 Ice Penetrator Shown with Bolt Heads Caught in Uprighting Device

identical to that used in test number one. This unit penetrated a total of 9.5 feet (which included 10 inches of snow cover) with a burn time of 143 seconds. Again, the hole diameter was quite large (on the order of 11-12 inches) indicating that this design directed too much energy around the periphery rather than in the direction of penetration. From our vantage point (approximately 125 feet away) we did not observe any apparent rotation of the penetrator while it was in the uprighting device. Once the penetrator was clear of the uprighting device, rotation may have been occurring, however, we were unable to see it. In any case, the hole was within a few degrees of vertical which indicates that there doesn't seem to be a problem with maintaining vertically.

Test number three again used a penetrator identical in configuration to that used in the first two tests. The final penetration depth was just over 6.5 feet with a burn time of approximately 132 seconds.

Test number four was another modification of the baseline nozzle configuration, (designated Mod 2 in Figure 6). The major differences were that the forward or central nozzle diameter was left at .141 inches and 2 of the 4 nozzles at 120 degrees were opened up from .085 inches to .141 inches. Calculated thrust of the Mod 2 was 2 pounds. Following ignition, the penetrator moved slowly downward then appeared to stop moving after penetrating about 2 feet of ice. Total burn time of the motor was 125 seconds. Post test inspection revealed that the central nozzle became clogged during the burn, which explained the lack of forward

progress. Depth of penetration was about 3 feet, hole diameter was 12-14 inches.

Test number 5 was an alternate ice penetrator configuration (designated as Alt 2 in Figure 6). In this design, the central nozzle was opened to .281 inches in diameter to greatly reduce the risk of clogging and to direct a majority of the exhaust (about 70%) through the central nozzle. This penetrator had a total of only 5 nozzles, 1 central, none at 60 degrees, and 4 at 120 degrees. Following ignition, the penetration appeared very rapid, with the motor dropping out of sight (i.e., completely traversing the length of the uprighter) in less than 30 seconds. Complete penetration was observed at just under 2 minutes, as evidenced by a rapid upsurge of water coming up through and overflowing the hole at the top of the ice. Total burn time was approximately 135 seconds. The hole diameter was noticeably smaller than on any of the previous tests, measuring about 7 - 7.5 inches in diameter. The actual ice thickness penetrated was 10 feet 4 inches, measured using a long vertical bar. Again, the hole produced was almost perfectly vertical.

Test number 6 utilized the identical configuration as Test number 4. Results were virtually identical to Test number 4 in that total depth of penetration was approximately 3 feet, and post test inspection revealed that the central nozzle had clogged. Figures 8 - 13 show photographs of actual Arctic testing.

4.2.2 Uprighter Test Results (Arctic)

A total of six uprighter units were shipped to the Arctic for

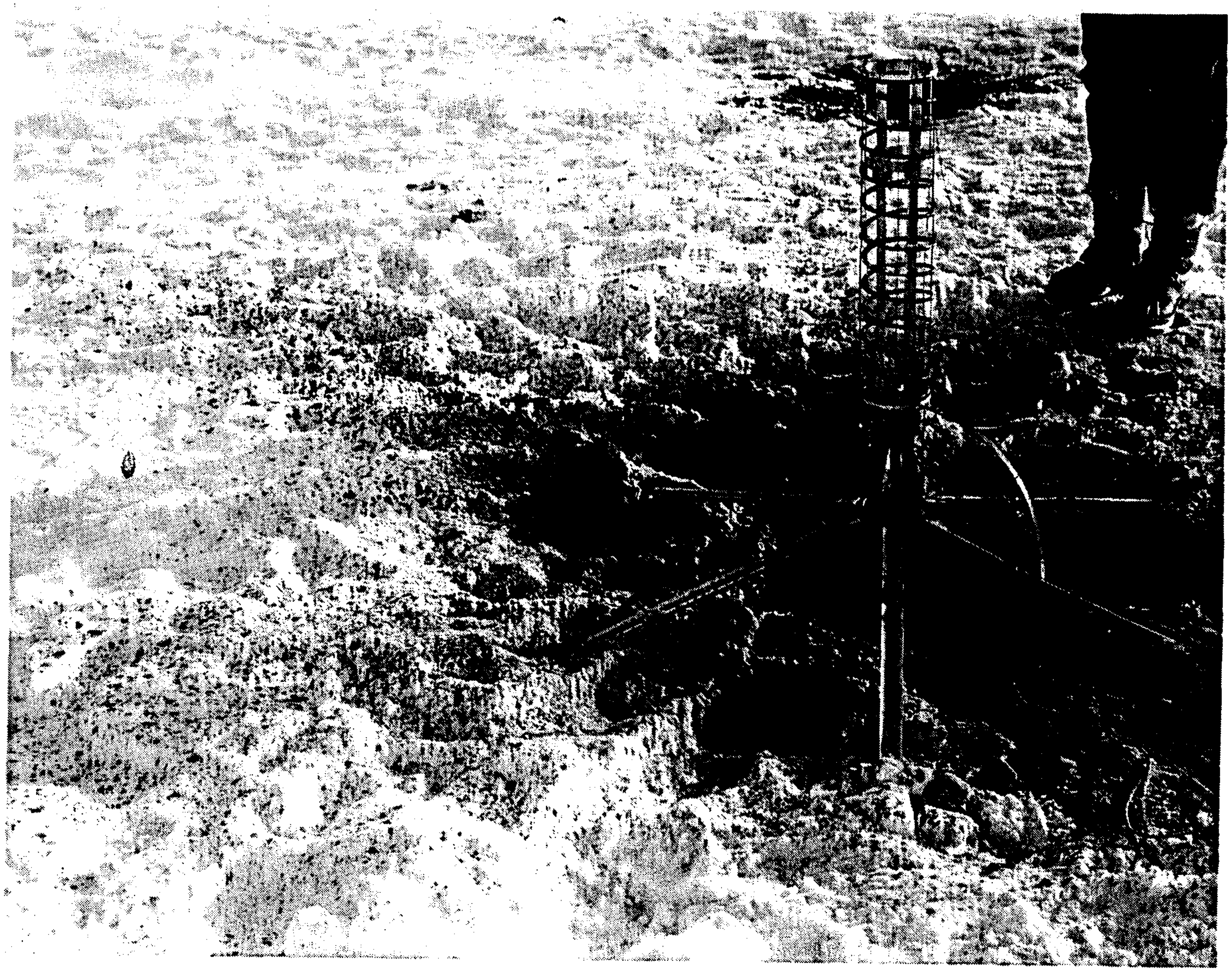

Figure 8 Post Test Photo - Arctic Test #2

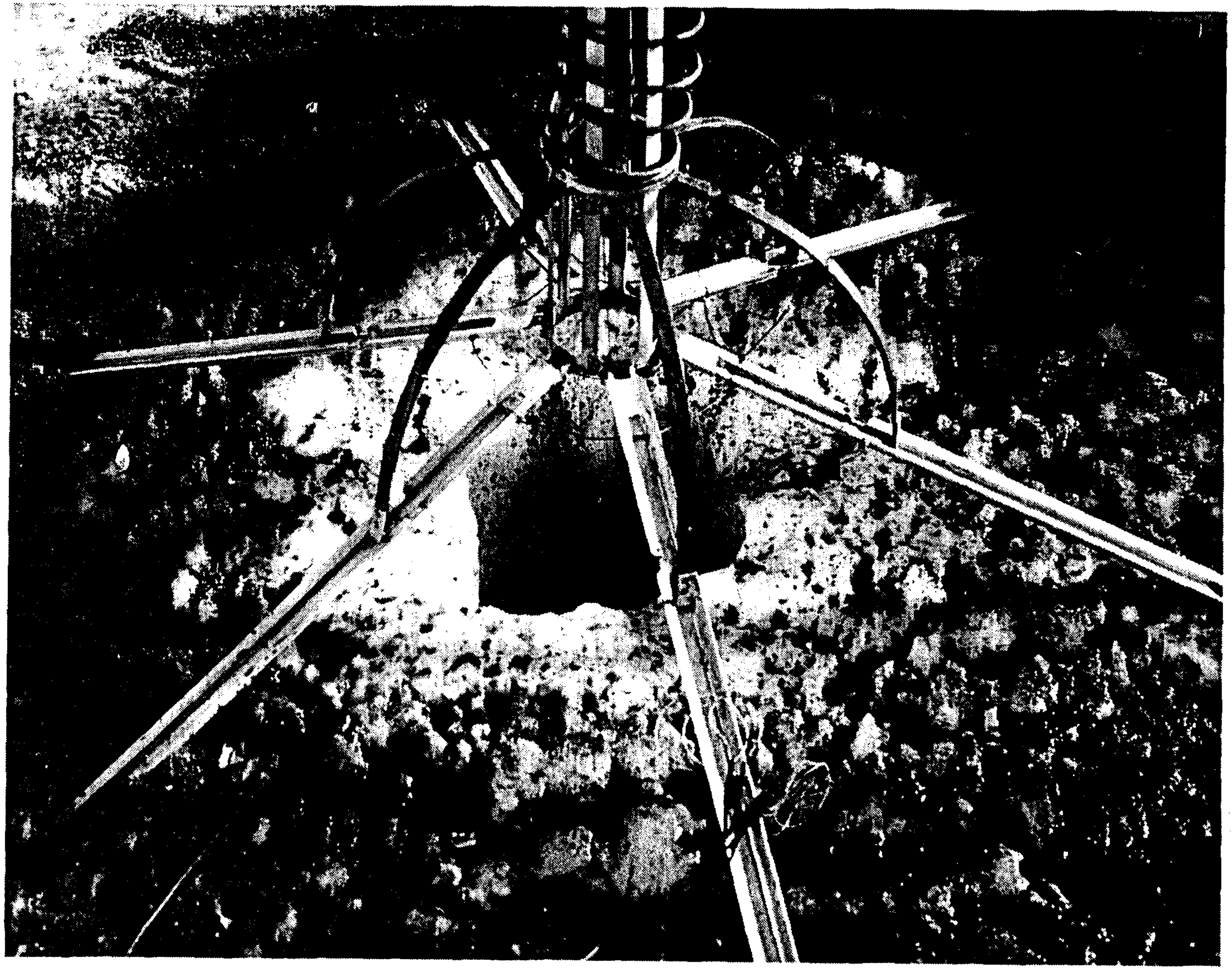

Figure 9 Post Test Photo - Arctic Test #3

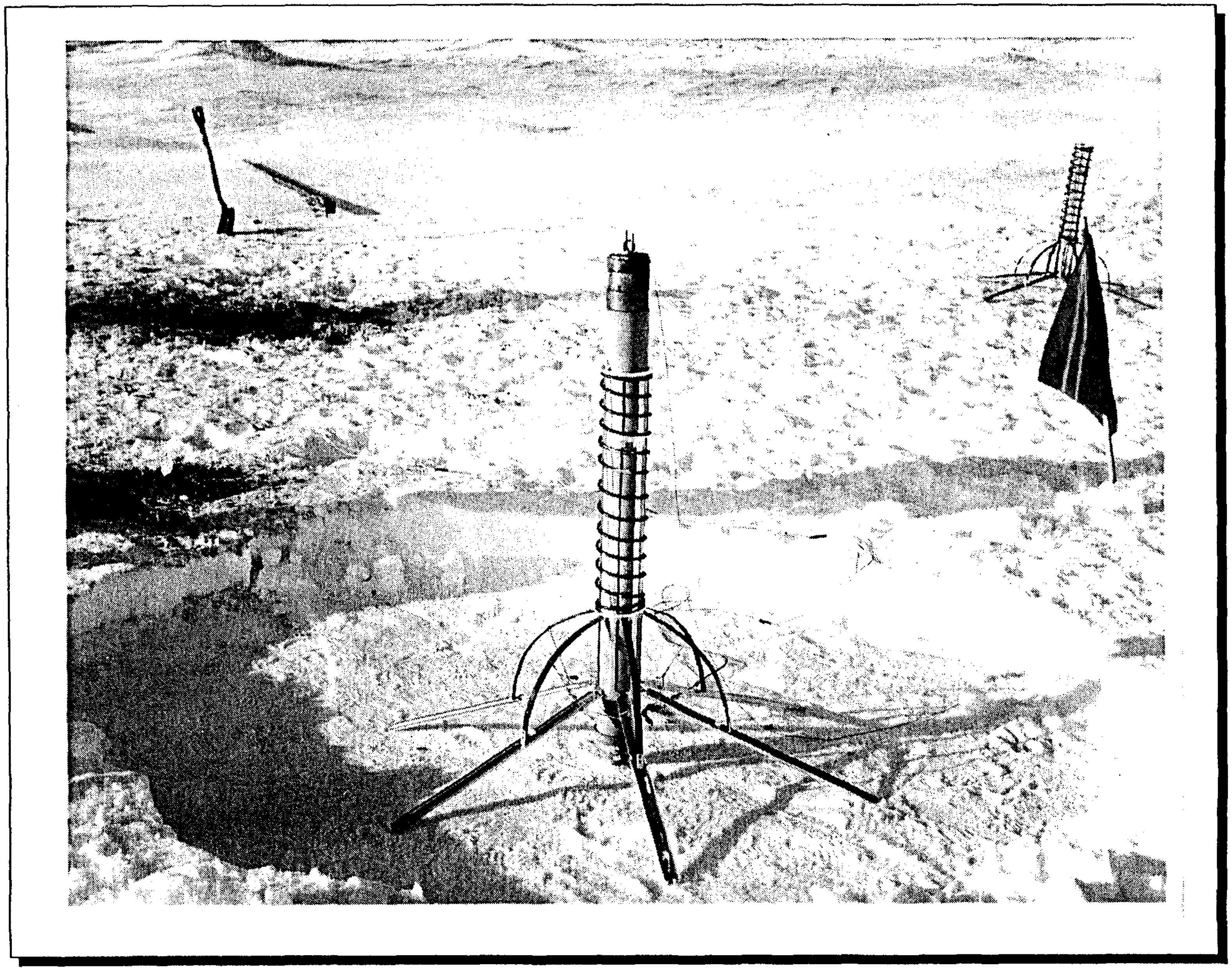

Figure 10 Pre Test Photo - Arctic Test #5

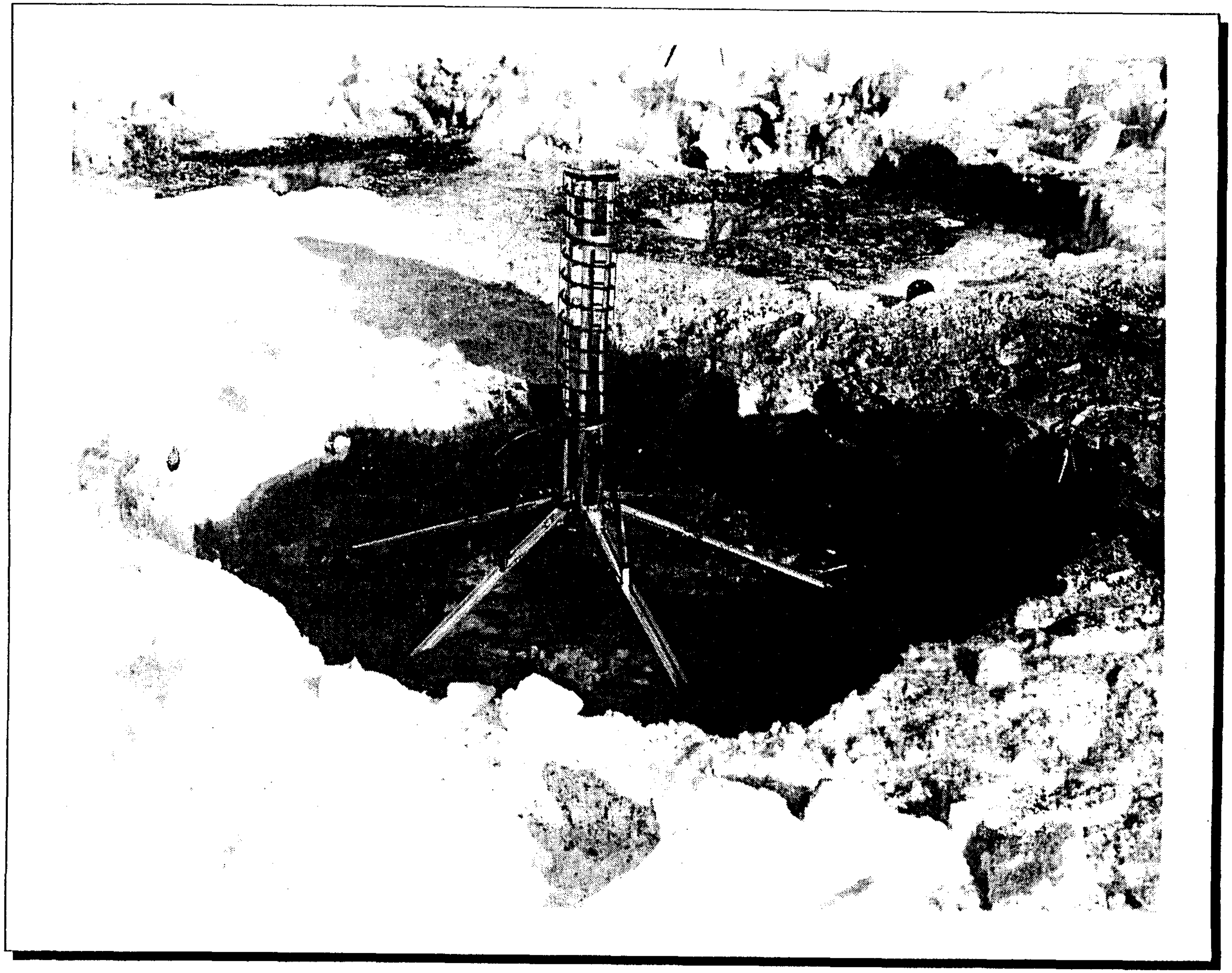

Figure 11A Post Test Photo - Arctic Test #5

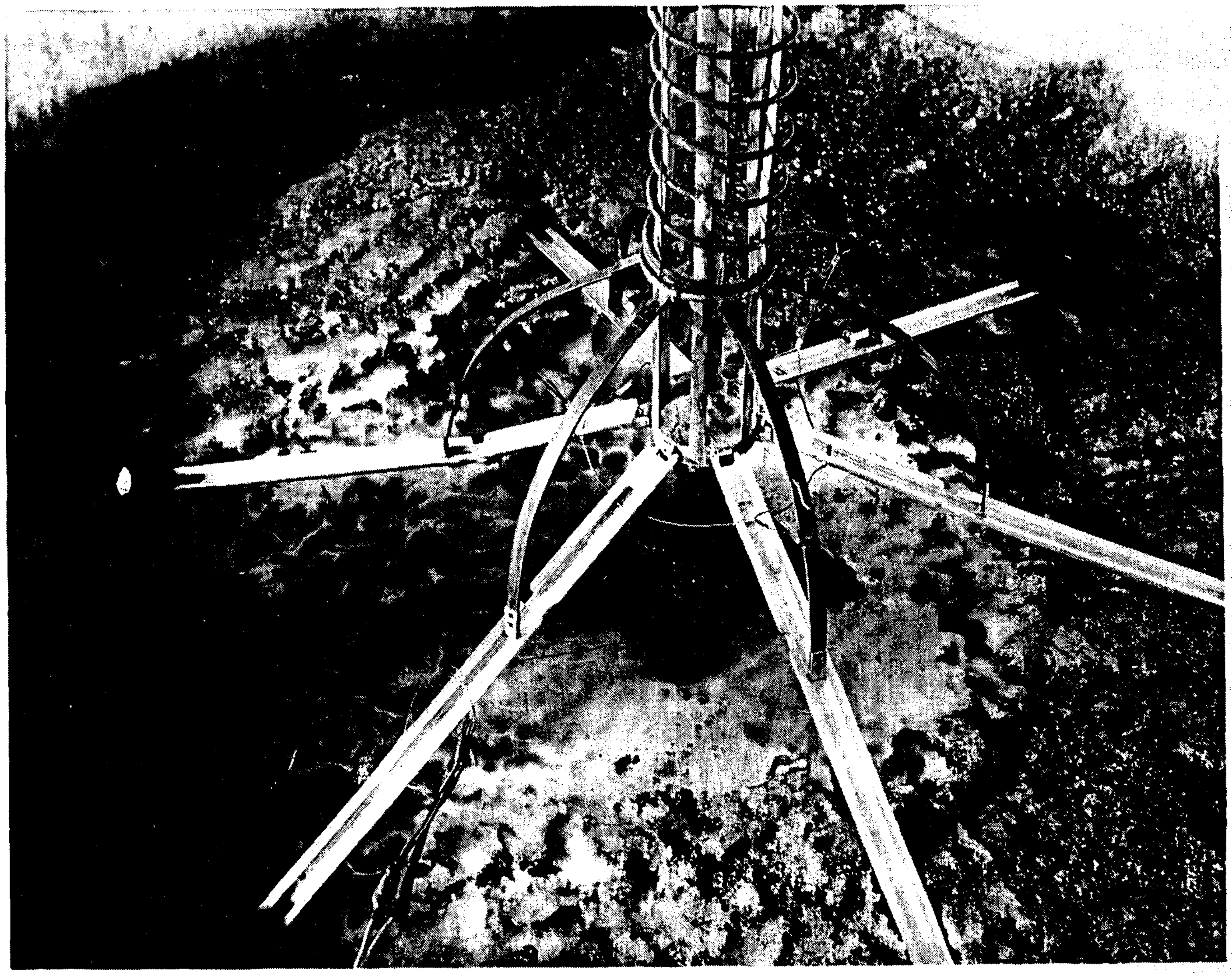

Figure 11B Post Test (Close Up) - Arctic Test #5

Figure 12 Post Test Hole Measurement - Arctic Test #5
(10 feet, 4 inches)

Figure 13 Pre Test Photo Showing Size Perspective

testing purposes. All six units were identical. Of the six shipped to the Arctic, one was damaged and sufficient time was simply not available to repair the unit in the field. For the 5 remaining units, test results are tabulated below:

- 2 units uprighted the payload to within a couple degrees of vertical with no apparent problems.
- 1 unit uprighted satisfactorily, however, after uprighting, one leg was bent approximately 15 - 20 degrees.
- 1 unit uprighted to 45 degrees and stopped. (This was the first unit tested. Following this test the damping was reduced for all subsequent tests.)
- 1 unit did not upright. The legs opened normally, however they simply drove into the soft snow without uprighting the penetrator.

Since there were 6 penetrators and only 5 functioning uprighting devices, one of the uprighting devices was reused for ice penetration test number 6.

5.0 UPRIGHTING A LARGE PAYLOAD

This research effort dealt with the analysis and testing of an "A" size ice penetrator and payload. The "A" size dimensions can be represented by a cylinder 36 inches in length, 4.87 inches in diameter, with a maximum weight of 50 pounds.

Since there may be other applications of this technology using significantly larger payloads, the following analysis was conducted

to assess the feasibility of autonomously uprighting a large payload.

5.1 Assumptions

It was assumed that the payload to be uprighted and delivered through the ice is cylindrical in shape. The following additional assumptions were made:

	Payload	Ice Penetrating System incl. Payload
Length	12.0 feet	14.5 feet
Diameter	21.0 inches	25.0 inches
Weight	2000 pounds	2500 pounds

The uprighting time (horizontal to vertical) shall be less than 4 seconds.

5.2 Analysis

A simplified diagram showing the external system configuration with dimensions is provided in Figure 14A.

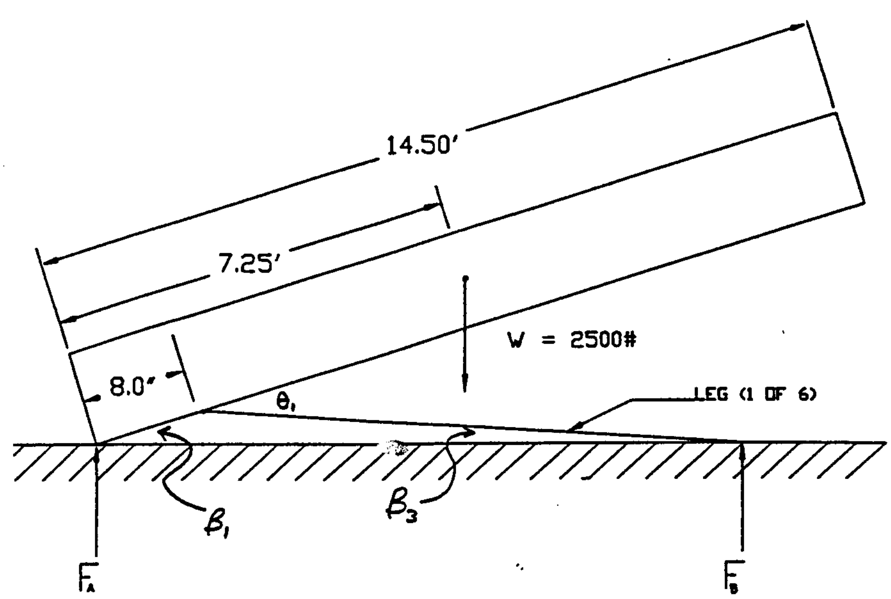

Figure 14A Uprighting System Configuration

Applying the basic equilibrium equations (assuming, for the moment, static conditions with θ_1= 15 degrees):

$$\Sigma_{Fy} = 0$$

$$F_A + F_B - 2500 = 0 \text{ and,}$$

$$\Sigma M_A = 0$$

$$(2500 \cos\beta_1)(7.25) - F_B(12.8 \cos\beta_3 + .67 \cos\beta_1) = 0$$

Letting θ_1= 15 degrees and applying the Law of Cosines and Law of Sines

$$\beta_1 = 13.75°$$

$$\beta_3 = 2.87°$$

Solving for F_A and F_B yields

$$F_B = 1309 \text{ Lbf}$$

$$F_A = 1191 \text{ Lbf}$$

Now, assuming a telescoping arm with ends mounted as shown in Figure 14B provides the righting force, and solving for the force

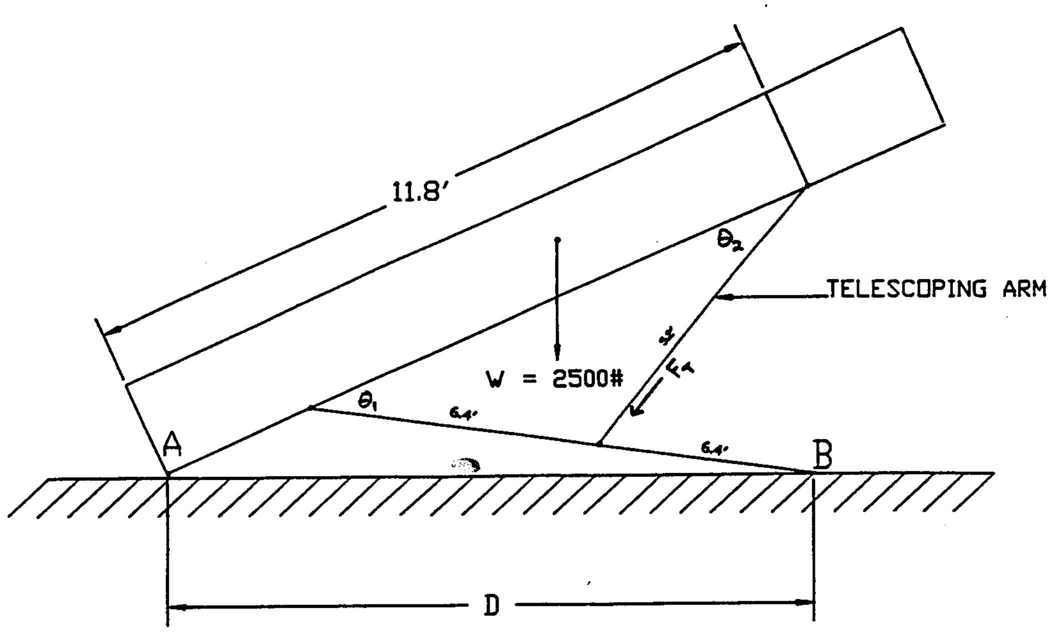

Figure 14B Uprighting System Shown with Telescoping Arm

required (F_T) yields:

$$\Sigma M_A = 0$$

$$(2500 \cos\beta_1)(7.25) - (F_T \sin\theta_2)(D) = 0$$

$$F_T = 4125 \text{Lbf.}$$

Thus the static force required (F_T) is 4125 pounds when $\theta_1 = 15°$. The amount of force supplied must be slightly higher and will depend upon the desired acceleration (uprighting time). Also note that the force F_T diminishes as θ_1 increases, going to zero when the penetrator is vertical.

In addition to the telescoping arm, a separate means of initially lifting the inert end of the device 3.4 feet off the ground (θ_1= 15 degrees) is needed. The force required is approximately 2500/2 = 1250 Lbf.

An example of a similar device designed and built by Thiokol to upright very large missile launchers (i.e., 12 feet diameter) is shown in Figure 15A & B. In this case solid propellant gas generators provide the motive force for both breakout and the telescoping arms to upright the buried missile launchers.

6.0 ANALYTICAL MODELING

The analytical model developed during Phase I was used to evaluate various nozzle design options and to select the optimum configuration for fabrication and testing. The baseline nozzle design (shown in Figure 2) was selected based upon trade offs between thrust, system weight and penetration efficiency.

The analytical model was updated following the two Phase I

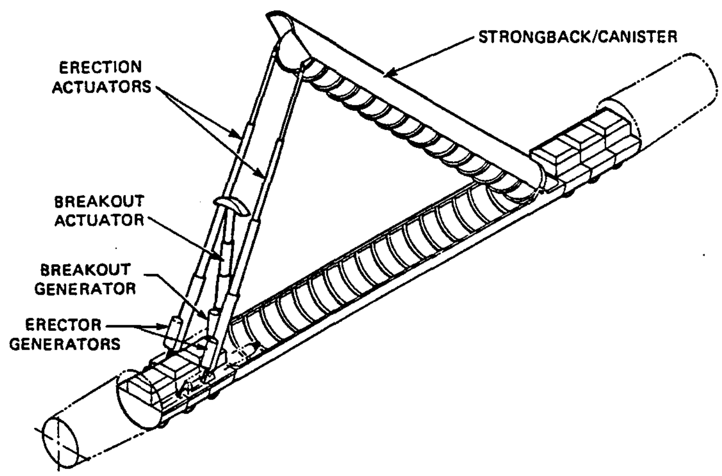

Figure 15A Buried Trench Erection Device Using a Thiokol Gas Generator

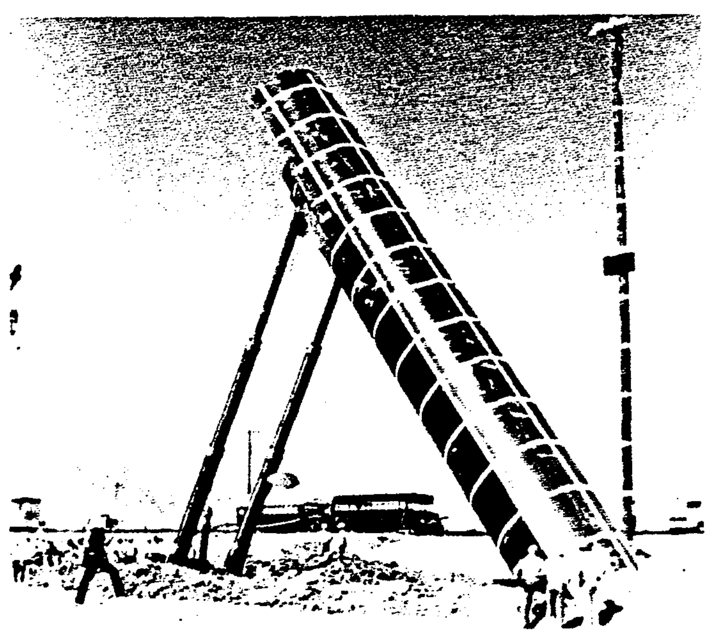

Figure 15B Buried Trench Erection Device Demonstration

penetration tests performed at Thiokol through 4 feet of ice during the fall of 1990. The nozzle configuration used in Phase II was significantly more complex, however, than that used in Phase I. Whereas the Phase I nozzle block consisted of 5 identical nozzles in a flat nozzle body, the Phase II nozzle was shaped in a truncated cone configuration with 9 nozzles, some of which were reverse acting.

The model predicted that the penetration rate of the baseline design was highly dependent upon total system weight. As can be seen in Figure 16, the model predicts a depth of penetration of just over 8 feet, based upon a penetrator/payload weight of 49 pounds (approximately 7 pounds of payload weight). Figure 17, however, predicts successful penetration through 10 feet of ice if the system weight is increased to 64 pounds (22 pound payload weight).

Results from the first in-house test showed the model to be fairly accurate. Penetrator weight was approximately 48 pounds, and depth of penetration was just under 8.0 feet.

In order to verify the model's performance predictions, the two additional in-house tests were performed with a payload of 25 pounds. Unfortunately, problems associated with the two in-house tests (i.e., the nozzle clogging and the frozen-in wire) prevented us from acquiring sufficient additional data to verify the model's performance with regard to the new nozzle.

Due to the absence of additional credible test data for the new nozzle configuration, two alternative designs were fabricated

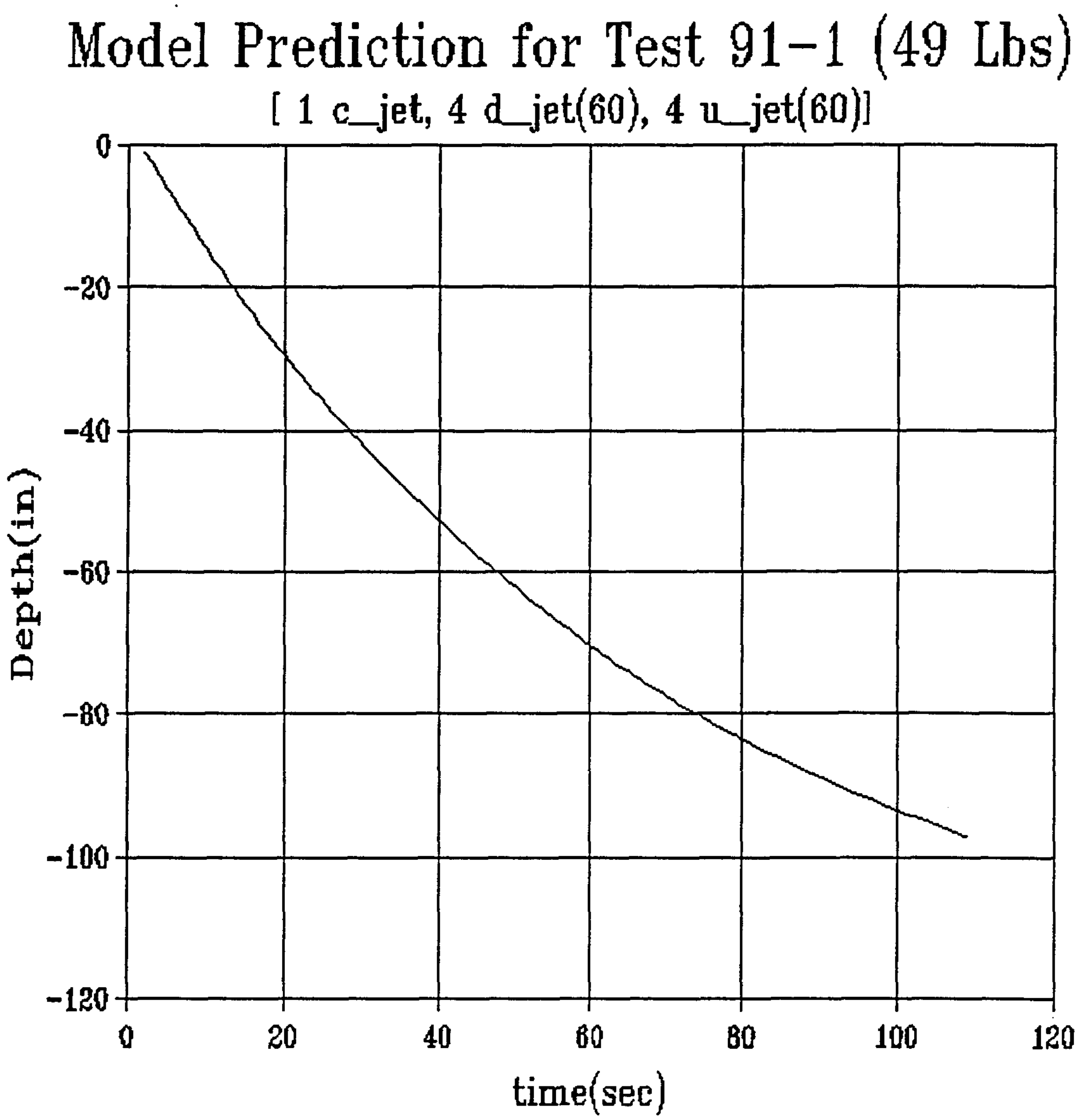

Figure 16 Predicted Penetration Rate
(Baseline design, 7 lb. payload)

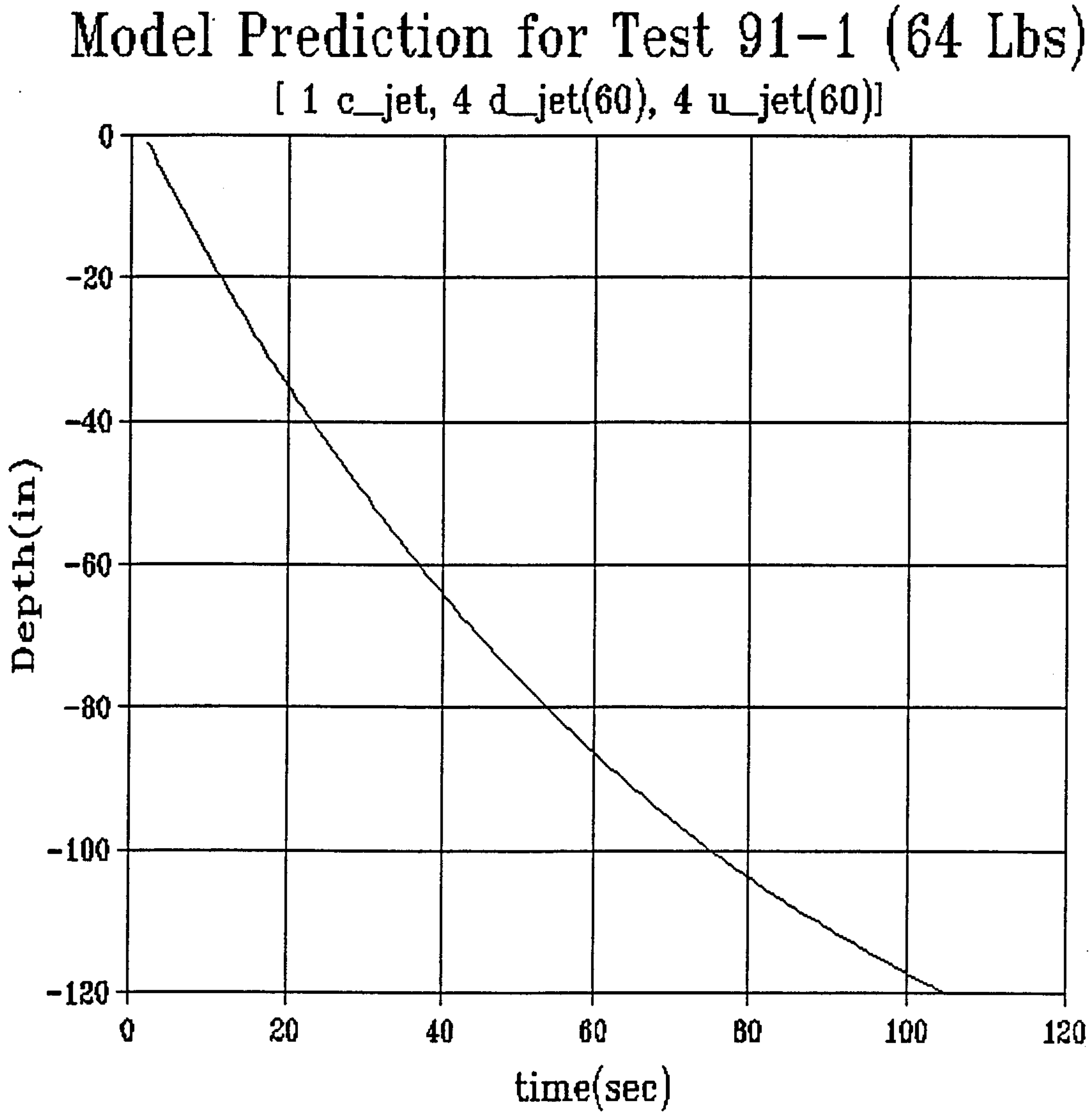

Figure 17 Predicted Penetration Rate
(Baseline design, 25 lb. payload)

for the Arctic tests. One of the alternatives (designed as MOD 2) was designed to quantify the effect of thrust on penetration rate. The other alternative (designed as ALT 2) was designed for risk mitigation. The ALT 2 design featured a very large central nozzle such that if nozzle clogging did become a problem in the Arctic, this design would have a very low probability of clogging. Figure 18 depicts the penetration rate for the ALT 2 design based upon the post-Arctic test validated model.

7.0 Conclusions/Lessons Learned

Based upon a successful field test under actual conditions in the Arctic, it appears that the overall concept of using a rapid thermal ice penetrator to deliver payloads through thick Arctic ice is a valid one. The testing demonstrated the following:

- That a properly designed solid propellant ice penetrator is capable of penetrating 10 feet of Arctic ice in under 2 minutes.
- That a lightweight, low cost, uprighting device can autonomously upright the penetrator from horizontal to vertical after it comes to rest on the ice surface.
- That the hollow tube uprighting device design provides sufficient guidance for the penetrator as it initially enters the ice such that verticality is maintained for the entire 10 foot thickness.

Although successful penetration was achieved, some areas were identified that require additional work.

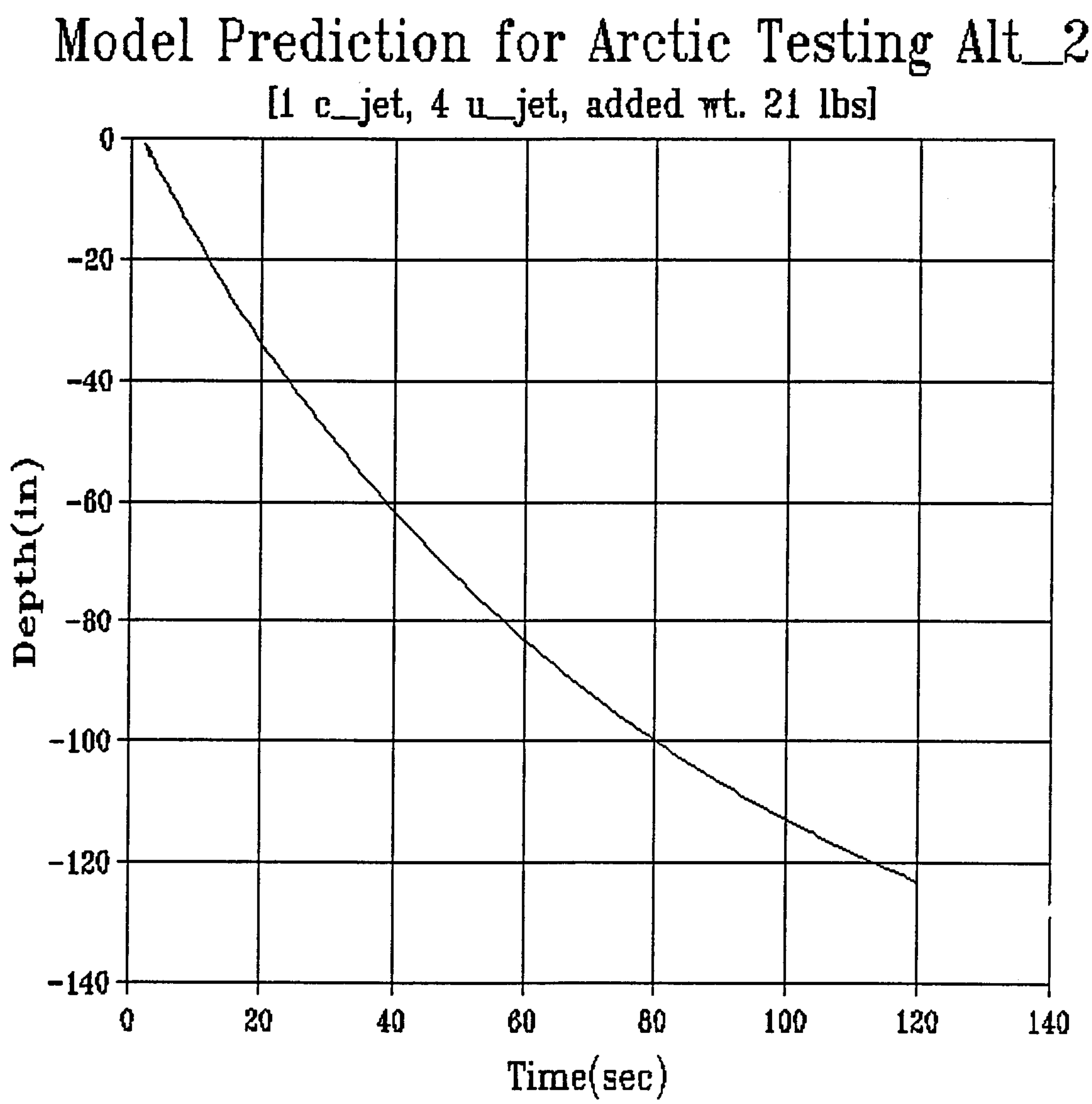

Figure 18 Validated Penetration Rate
(Alt 2 design)

As might be expected, the most efficient penetrator directed most of its exhaust through the center nozzle. Such a design may require further reductions in chamber pressure to meet thrust goals.

Higher energy propellants are available that would reduce the weight (and volume) of propellant required. Such a higher energy propellant needs to be tested.

An improved method of adjusting the damping (drag) of the spring force in the uprighting device needs to be designed. Although it functioned properly after minor adjustments in the field, the method does not lend itself to repeatable results in mass production.

Although the uprighting device seemed to work well on a relatively hard packed ice/snow surface, on soft snow the legs simply drove into the snow without uprighting the penetrator. To eliminate this problem, some means of increasing the effective surface area of the legs should be devised.

A majority of the lessons learned did not deal directly with the hardware per se, but had to do with testing in the Arctic environment itself. Enough cannot be said for the experience gained from spending a few days in -30°F to -40°F temperatures trying to set up and perform a test at a remote ice camp.

In general, everything simply took longer than planned. For example, in order to simplify the shipment of the test hardware to the Arctic we had planned to mate the uprighting devices with the ice penetrators, as well as install the release mechanisms all at

the ice camp. Based upon having performed this operation several times in our own facility, we estimated that this operation could be performed on all 6 penetrators in 1 to 2 hours. In fact, it took almost a half a day just to open all the shipping crates. At -30°F the battery powered portable tools we brought to open the boxes operated at reduced capacity and quickly ran out of power. When we attempted to tape certain items such as wire leads not one of the three different kinds of tape we had brought would adhere in the cold. In addition, the method of placing and holding the release band around the uprighting device required the simultaneous lining up of several components such that a small dowel pin could be slipped into place. While this operation had been performed on numerous occasions in our shop with no apparent problems, we could not attain the required physical dexterity with gloves on and we were not able to keep our gloves off long enough to complete the task. The end result was that an alternate method of attaching the release mechanism was devised in the field which functioned adequately.

The overall lesson learned regarding Arctic testing was that every attempt should be made to ship test units to the Arctic fully assembled. Assembly work that requires any amount of physical dexterity (i.e., must be performed with a bare hand) should be avoided.